# Very Small Asymmetries and the Weak Interaction

Greg Mitchell
Physics Division
Los Alamos National Laboratory

The laws of physics describe four interactions:

**gravity**

**electromagnetism**

**strong**

**weak**

The Standard Model of electroweak interactions has been extensively tested, and is remarkably successful.

The weak interaction is in many ways well-understood,

($W^{\pm}$ and Z exchange, masses known to 4 significant figures)

but not at low energy scale.

**Weak interactions** can be leptonic, semi-leptonic, non-leptonic

They can change lepton and quark flavor

But flavor conserving, neutral current weak interactions are difficult to observe at low energy (small ▯, obscured by EM interactions)

$\Rightarrow$ parity violation

Parity violation in an experiment must be due to the weak interaction

Example: in a fixed target experiment, □ changes for reversal of incident beam spin

**Asymmetry** - a way to observe a difference in cross-sections without making an absolute measurement

$$A = \frac{\square_1 \, \square \, \square_2}{\square_1 + \square_2}$$

Weak coupling/amplitudes are small ($G_F$)

$\Rightarrow$ *A* can be small

systematic errors

especially spin-correlated backgrounds,
beam motion/energy/intensity

statistical errors

observe <u>many</u> events

$$A = \frac{N_1 - N_2}{N_1 + N_2} \quad \Rightarrow \quad \delta_A \approx \frac{1}{\sqrt{N_1 + N_2}},$$

so $\quad \delta_A = 10^{-8} \Rightarrow N_1 + N_2 \approx 10^{16}$

To observe $10^{16}$-$10^{17}$ events in a reasonable time, use **current mode** (i.e. integrating) detectors

MHz to GHz event rates, measure total signal in a detector --- summed voltage/current/charge rather than individual pulses

$$A = \frac{Q_1 - Q_2}{Q_1 + Q_2} \quad Q = \sum_i^N q_i \quad \sigma_A{}^2 \approx \frac{\sigma_Q{}^2}{2\langle Q^2 \rangle}$$

if all $q_i = q,\ \sigma_Q = q\sqrt{N}$ and $\langle Q^2 \rangle = (qN)^2$

$$\Rightarrow \ \sigma_A{}^2 = \frac{1}{2N}$$

## If instead the $q_i$ have some distribution:

$$A = \frac{Q_1 - Q_2}{Q_1 + Q_2} \qquad Q = \sum_i^N q_i \qquad \sigma_A^{\ 2} \approx \frac{\sigma_Q^{\ 2}}{2\langle Q^2 \rangle}$$

$$\sigma_Q^{\ 2} = q^2 \sigma_N^{\ 2} + N^2 \sigma_q^{\ 2} = \left(q\sqrt{N}\right)^2 + N^2 \sigma_q^{\ 2}$$

$$\sigma_A \approx \frac{1}{\sqrt{2N}} \sqrt{1 + \frac{\sigma_q^{\ 2}}{\langle q^2 \rangle}}$$

Distribution of the observed charge/current/voltage for a single event can be due to:

- deposited energy variations with angle/geometry
- collection efficiency variation with location/angle
- shot noise in charge collection/photoelectron creation

Careful design can keep this effect to ~10%

Requirement for low noise in detectors & electronics
No threshold, discriminators---everything gets ‘counted’
Noise can be correlated with spin, false asymmetry

current mode detectors

very small asymmetries

parity violation

**weak interaction**

Two current mode parity violation experiments in development:

$\vec{n} + p \rightarrow d + \gamma$ at LANSCE

Qweak at Jefferson Lab

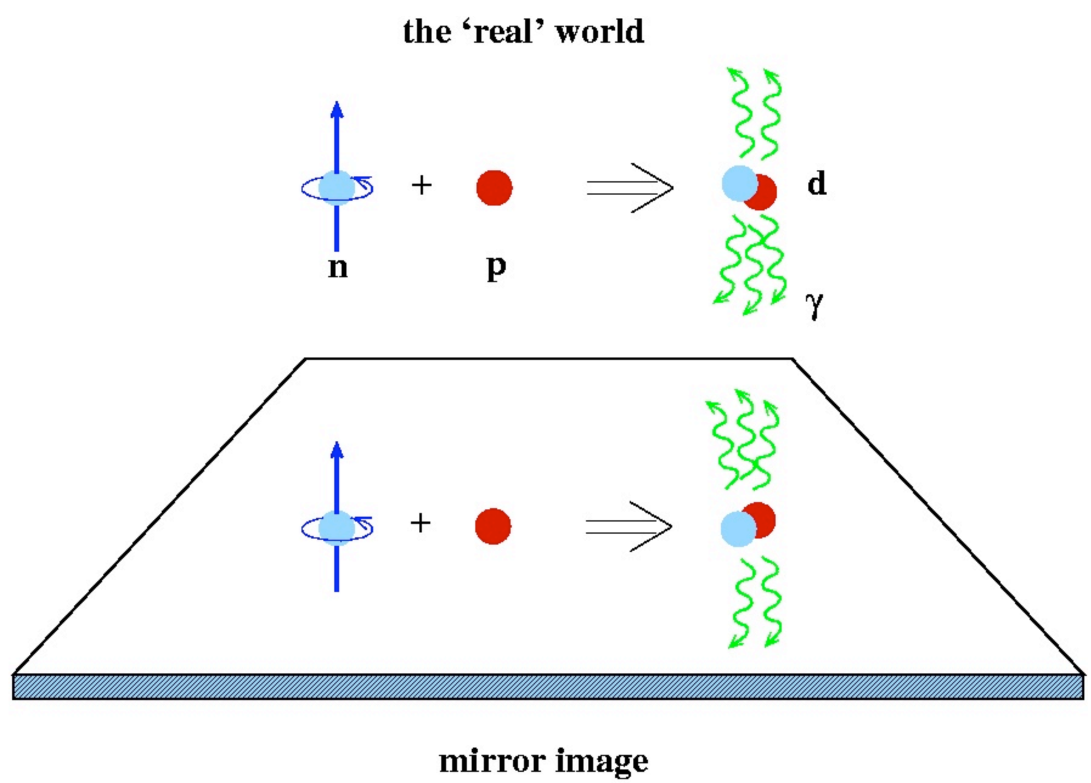
## $\vec{n} + p \rightarrow d + \gamma$ at LANSCE

NPDGamma will measure $A_\gamma$, the parity-violating asymmetry in the distribution of gamma-rays emitted in capture of polarized cold *n* by para-$H_2$

If the up/down $\gamma$ rates differ, parity is violated

Expected asymmetry: ~ - 5 x $10^{-8}$

Goal experimental error: 0.5 x$10^{-8}$

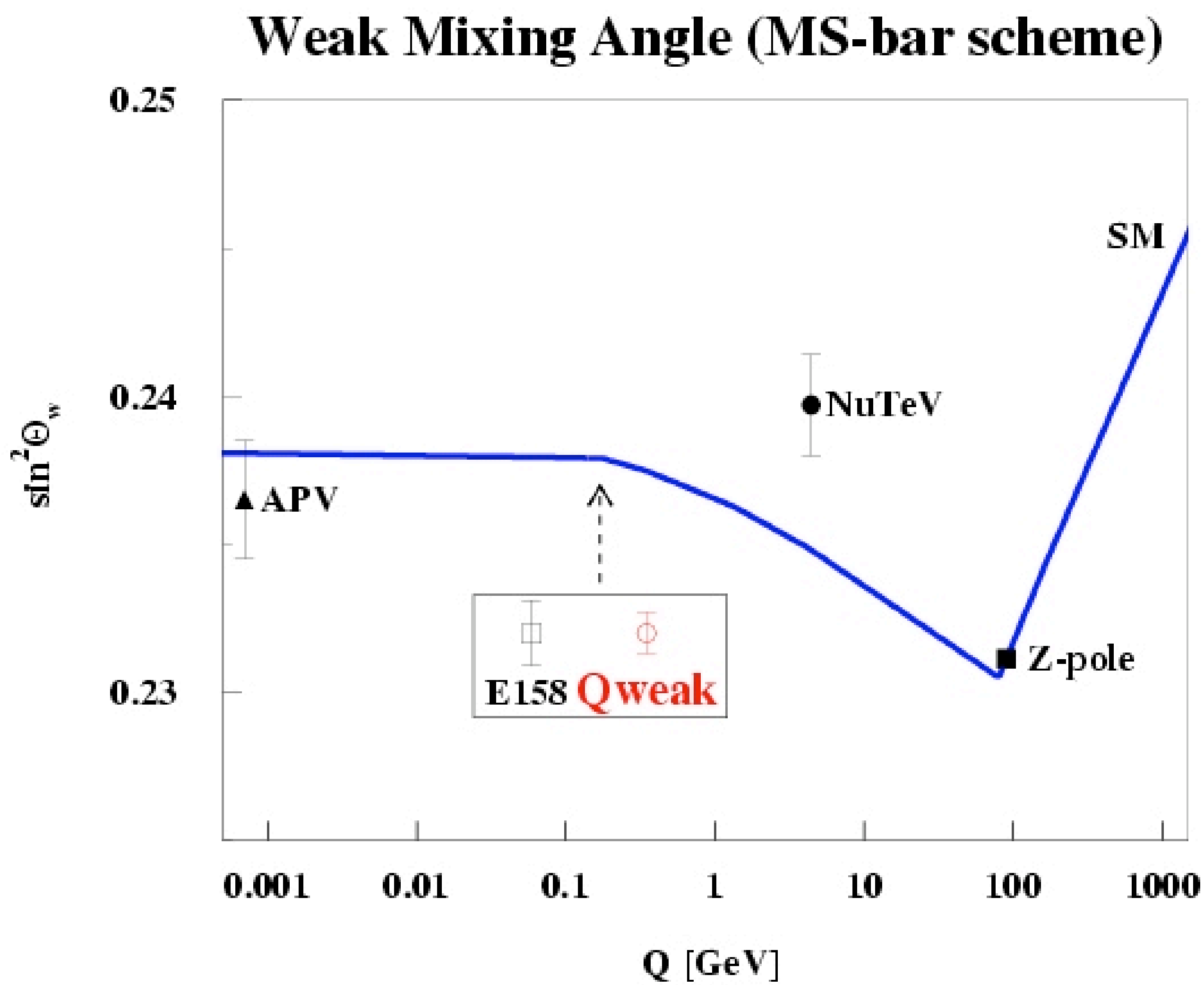


Measure the parity-violating asymmetry in
e-p elastic scattering at $Q^2 = 0.03\ \mathrm{GeV}^2$ to 4% relative accuracy

Extract the proton weak charge: $Q^p_{weak} = 1 - 4\sin^2\theta_W \sim 0.072$

# JLab E02-020

## Running of $\sin^2\theta_W$ in the Standard Model




[plot courtesy J. Erler, A. Kurylov, M.J. Ramsey-Musolf, Phys. Rev. **D68** 016006 (2003)]

# Experimental Similarities

- study of the weak interaction at low energy (protons/neutrons, not quarks)
- ppb precision
- observe parity violation in an asymmetry between incident states of beam polarization
- polarized beam on unpolarized target
- rapid (pulse-to-pulse) spin reversal
- large liquid hydrogen (proton) target
- current mode detectors

# Measurement of the Parity-Violating Gamma Asymmetry $A_\gamma$ in the Capture of Polarized Cold Neutrons by Para-Hydrogen,

$$\vec{n} + p \rightarrow d + \gamma$$

J.D. Bowman (Spokesperson), G.S. Mitchell,
J.M. O'Donnell, S.I. Penttila, P.-N. Seo, W.S. Wilburn,
V.W. Yuan
Los Alamos National Laboratory

S.J. Freedman, B. Lauss
University of California, Berkeley

T.B. Smith
University of Dayton

E.I. Sharapov
Joint Institute for Nuclear Research, Dubna

G.L. Jones
Hamilton College

M. Gericke, M. Leuschner, B. Lozowski, H. Nann,
S. Santra and W.M. Snow
Indiana University

T. Ino, Y. Masuda, and S. Muto
KEK National Laboratory, Japan

C. Gillis, S.A. Page, W.D. Ramsay
University of Manitoba and TRIUMF

T.E. Chupp, K.P. Coulter
University of Michigan

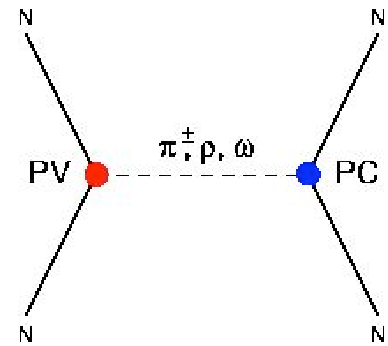
T.R. Gentile
National Institute of Standards and Technology

M. Dabaghyan, F.W. Hersman and H. Zhu
University of New Hampshire

D. Desai, G.L. Greene
University of Tennessee and Oak Ridge National Laboratory

R.D. Carlini
Thomas Jefferson National Accelerator Facility

# The Hadronic Weak Interaction

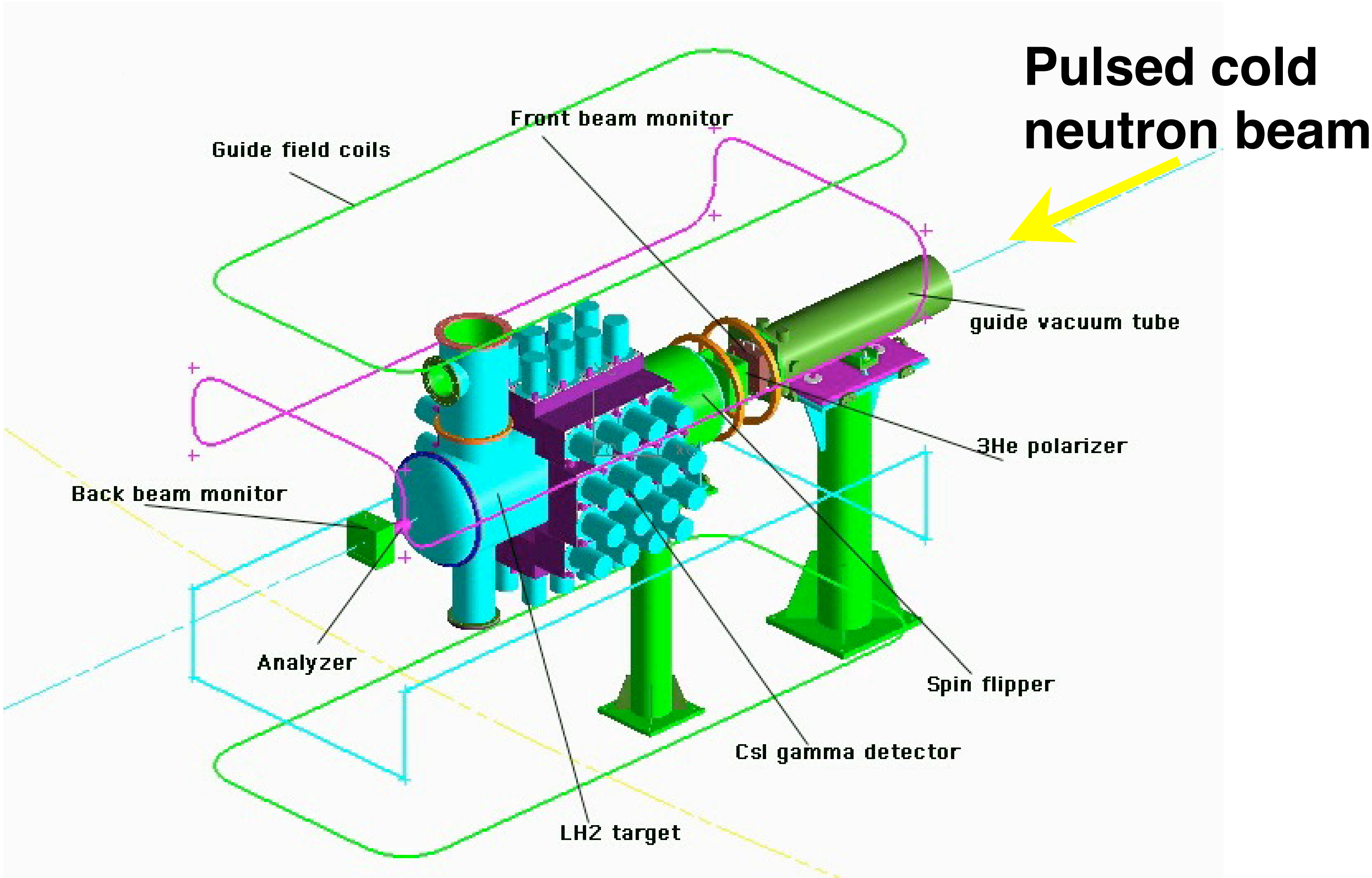



$$A_{\gamma} = \frac{1}{P_n}\frac{N_u - N_d}{N_u + N_d} \approx -0.11 f_{\pi} \approx -5 \times 10^{-8}$$

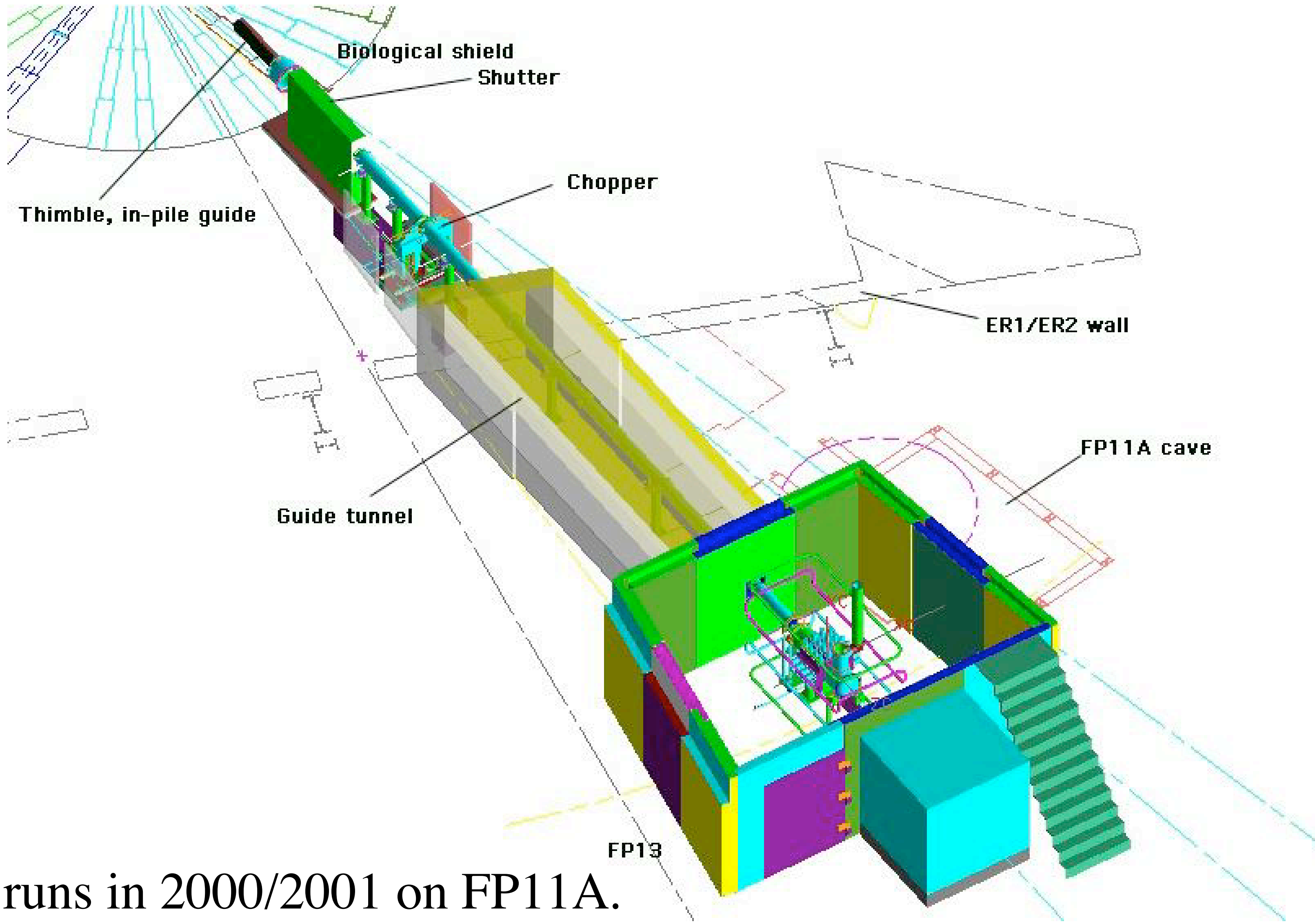
- The pion is the lightest and longest range meson.
- The pion coupling is generated by weak neutral currents.
- $\vec{n} + p \rightarrow d + \gamma$ isolates $f_{\pi}$. Negligible contributions from other mesons.
- No uncertainty from nuclear wave functions. Strong two-body solvable with small (5 %) uncertainties.
- Previous determinations of $f_{\pi}$ disagree. (Units of $10^{-7}$.)
  - DDH reasonable theoretical range 0 - 11.4, best value 4.5.
  - $^{18}F$ experiment gives 0 ± 3.
  - $^{133}Cs$ anapole moment gives 10 ± 4.
  - PV in compound nuclei gives 12 ± 2.
- Goal: Measure with a statistical uncertainty of 0.5 (10% of expected size) and negligible systematic uncertainty.

LANSCE at Los Alamos NATIONAL LABORATORY

# Drawing of NPDGamma Apparatus



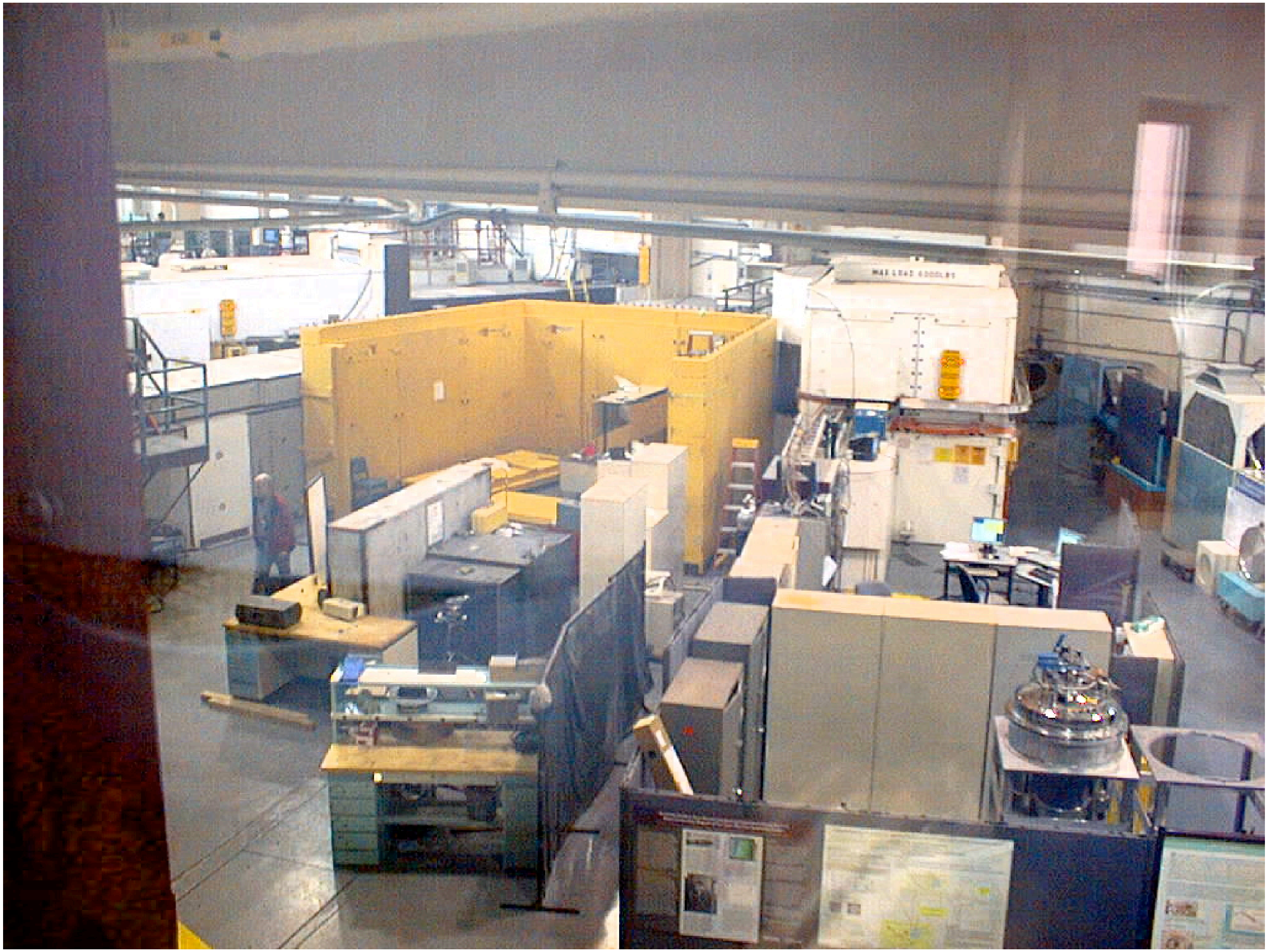
# NPDGamma Setup on FP12



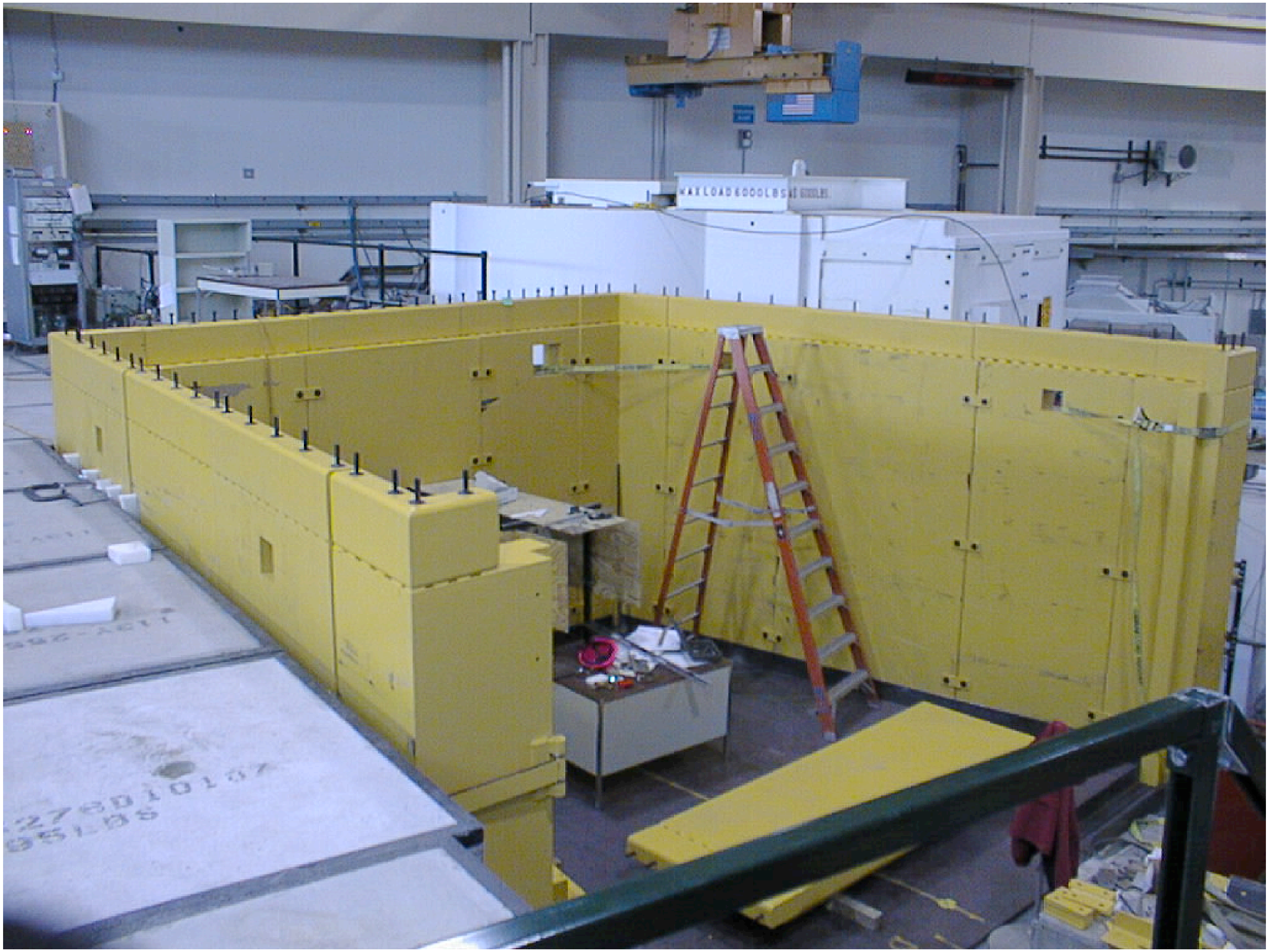

Test runs in 2000/2001 on FP11A.

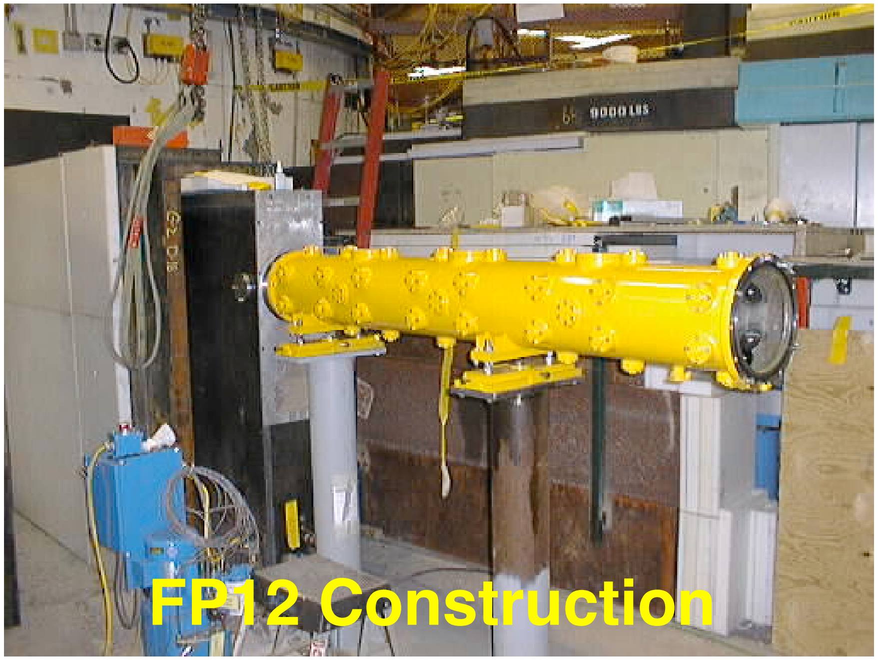
$A_{\gamma}$ with nuclear targets: raw $\sigma_{stat} \sim 2x10^{-6}$ in 8 hrs/target.

# NPDGamma FP12 Progress, November 2003



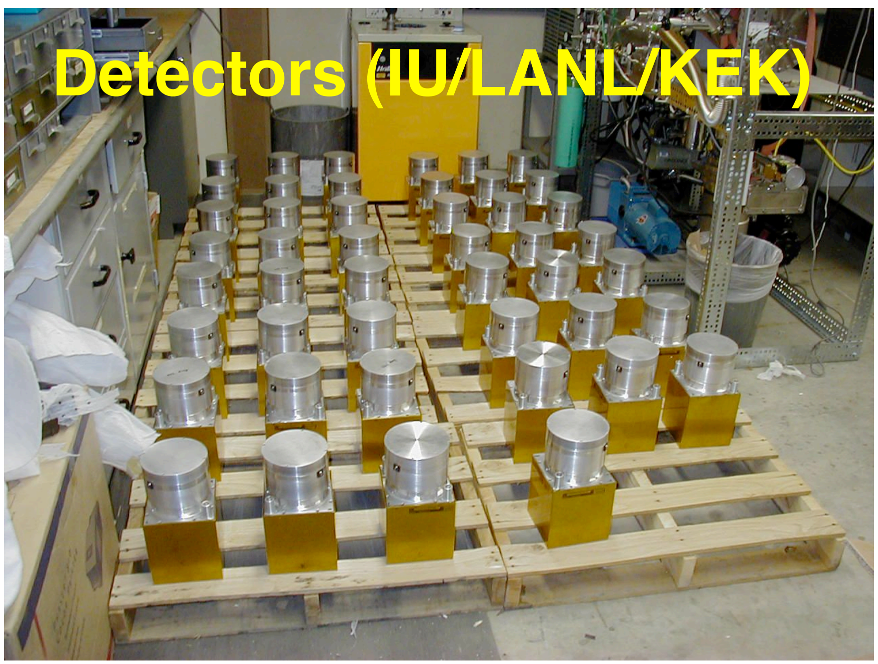
# NPDGamma FP12 Progress, November 2003





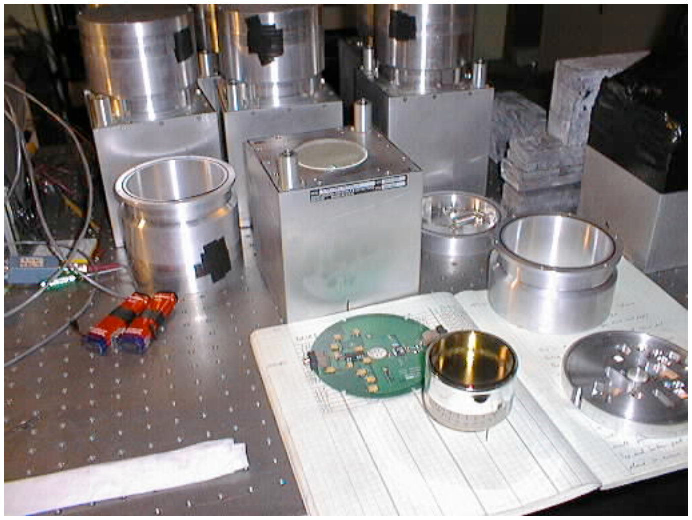
FP12 Construction

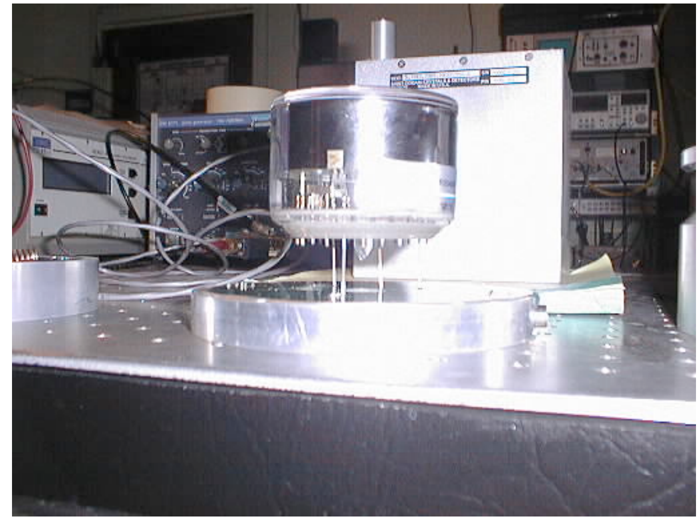
$^3$He Polarizer (NIST, UM)

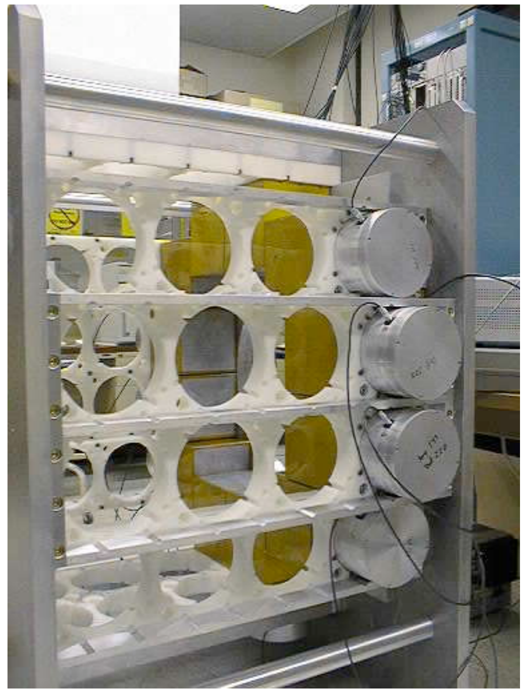


Detectors (IU/LANL/KEK)

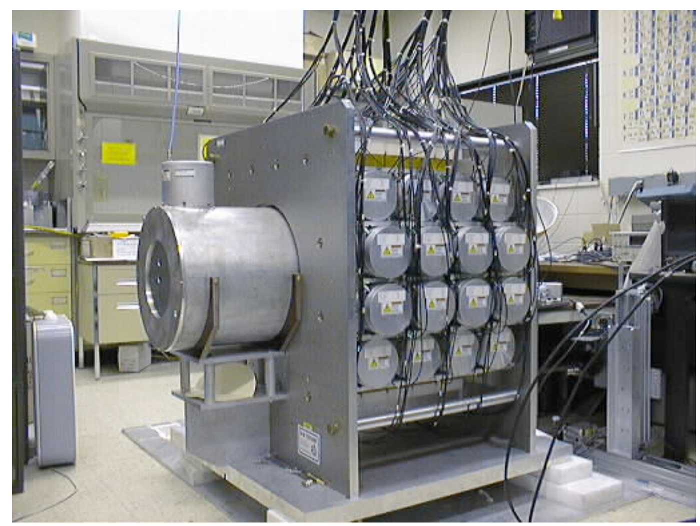
Detector Stand (Manitoba, TRIUMF)

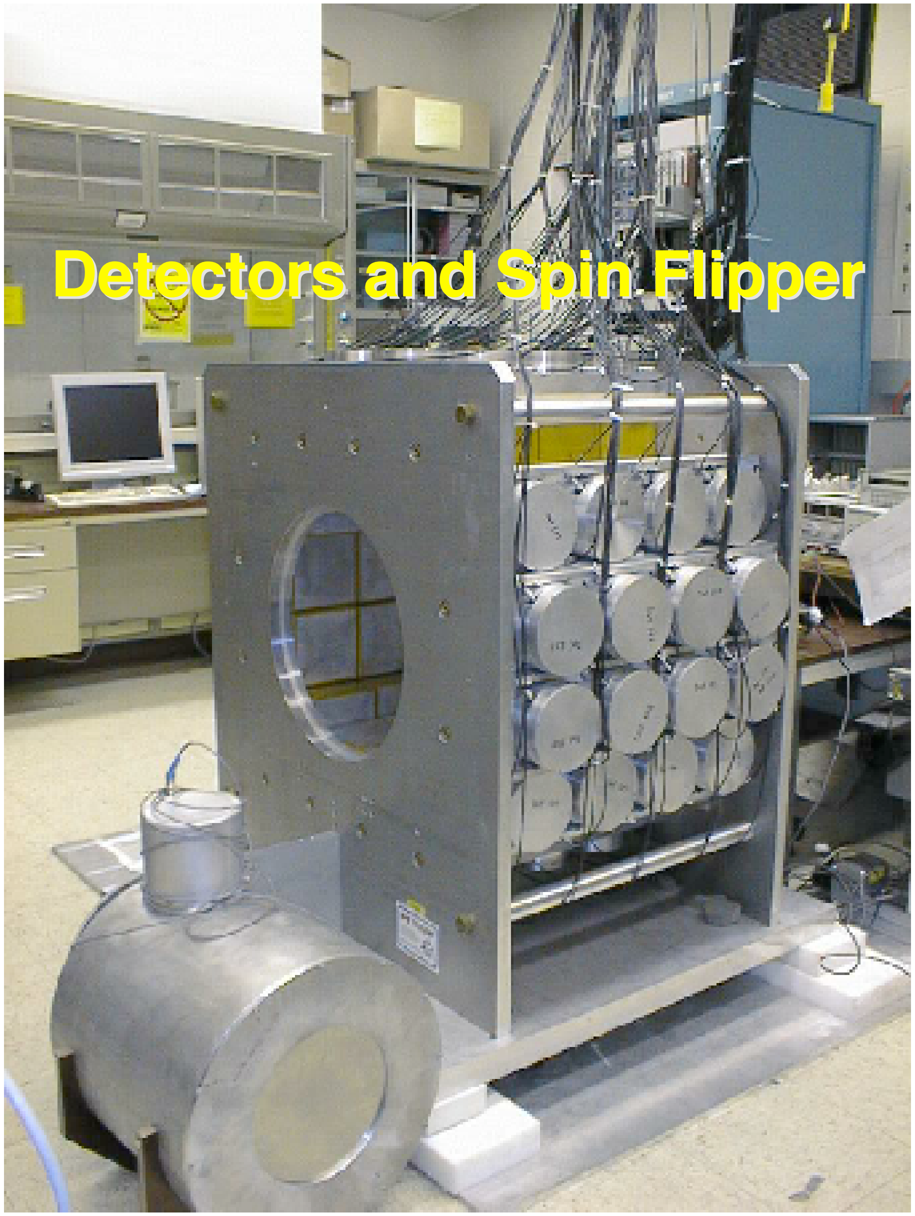


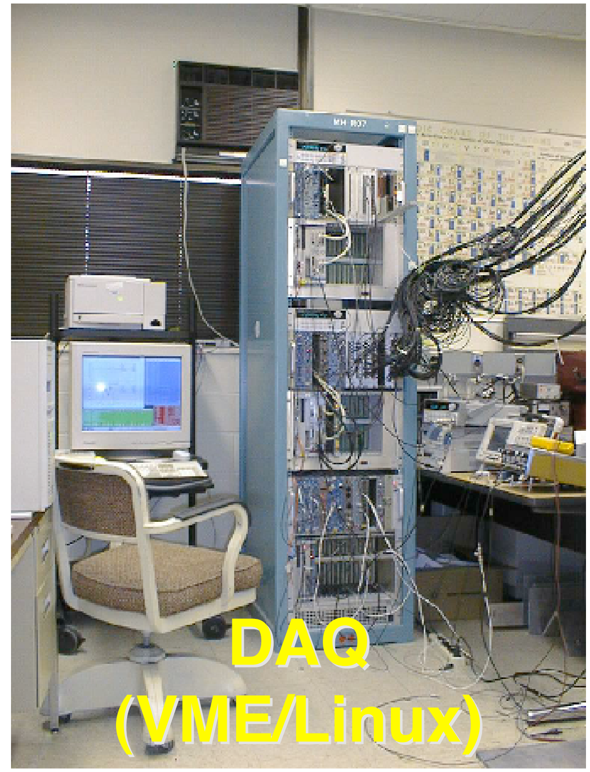


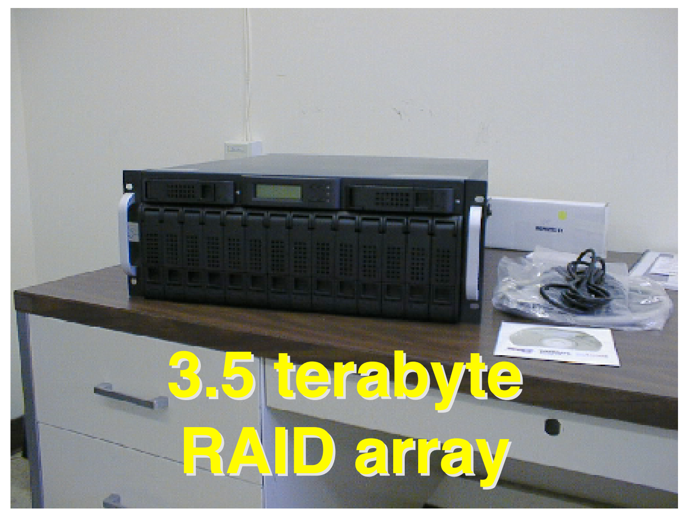



GERMANY

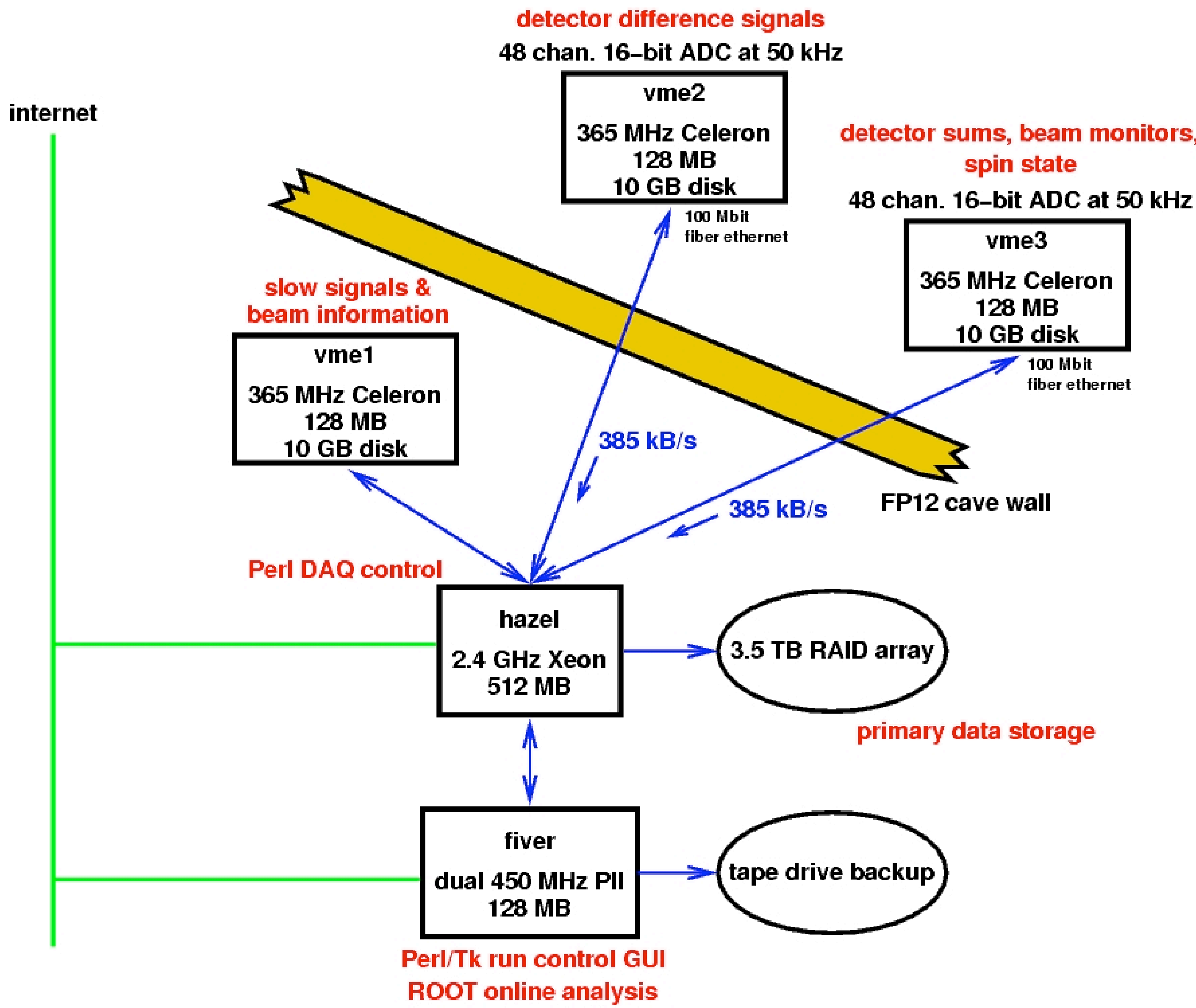



Detectors and Spin Flipper


DAQ
(VME/Linux)


3.5 terabyte
RAID array

# NPDGamma Data Acquisition

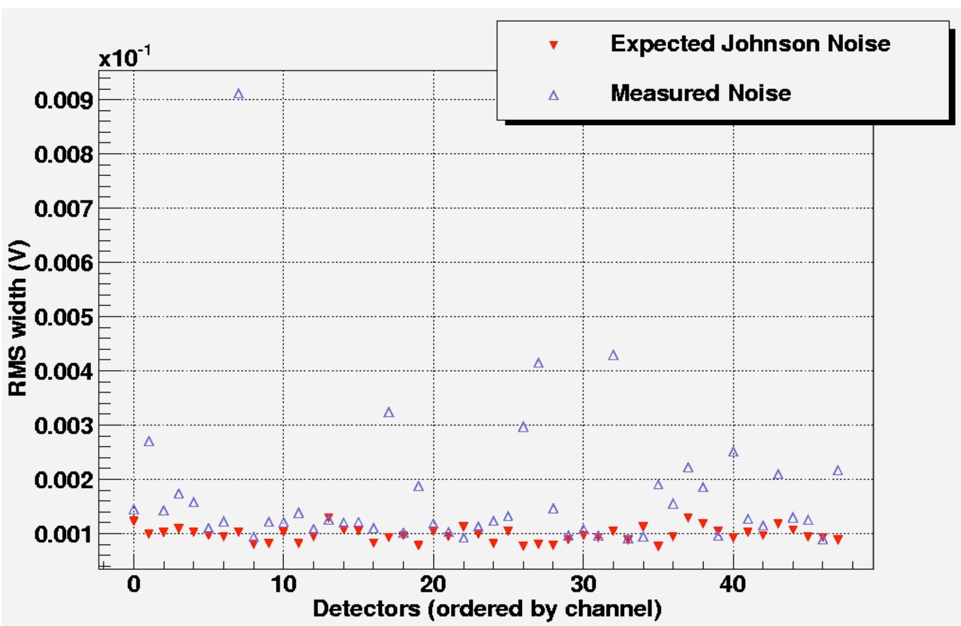


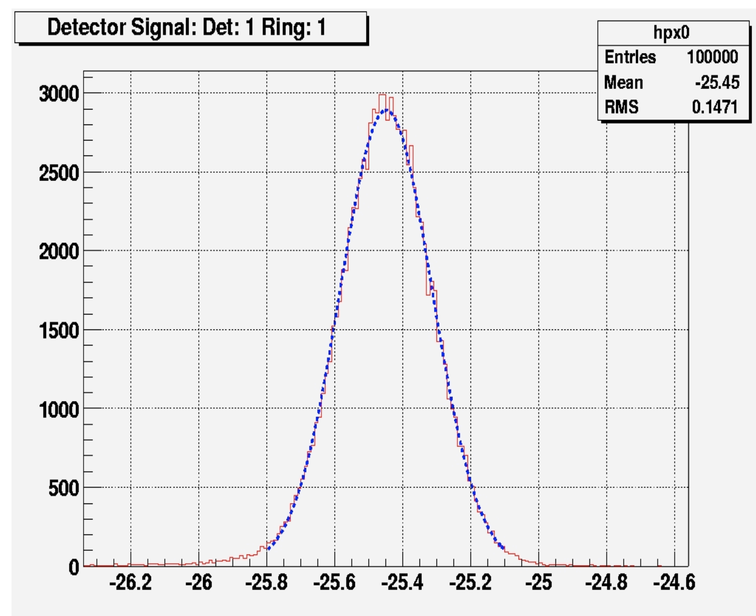
# Detector Noise Tests

**The detector pre-amplifier was designed to operate close to the level expected from thermal fluctuations.**

**The predicted total noise in the preamplifier is**

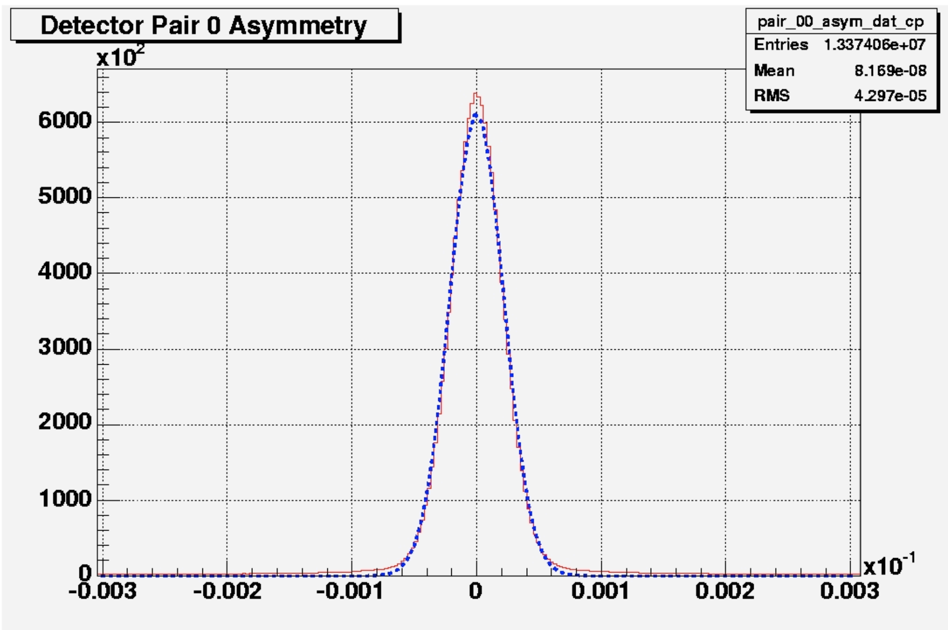
$$S\left(\sqrt{i^2_{johnson} + i^2_{amp}}\right) \square\, 21\, fA/\sqrt{Hz} \quad \square \quad \square\, 0.1\, mV \quad \textbf{RMS}$$

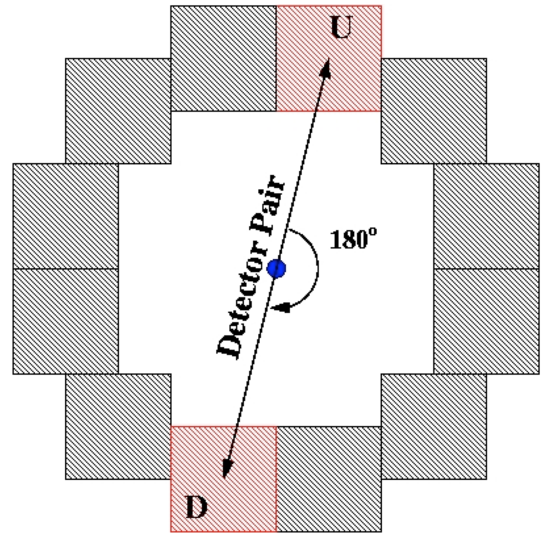


# Additive & Multiplicative Asymmetry due to Electronic Noise

**The time needed to measure the additive asymmetry to the $5\times10^{-9}$ level due to electronic noise is ~ 3 hours.**




$$A_{\gamma}(t) = \frac{U_{\uparrow} - D_{\uparrow} - (U_{\downarrow} - D_{\downarrow})}{U_{\uparrow} + D_{\uparrow} + U_{\downarrow} + D_{\downarrow}}$$

$$(\text{where } \uparrow,\downarrow = \text{Neutron Spin})$$

**Need a signal into the vacuum-photodiode to see a multiplicative effect. For beam-on or LEDs on, measurement time is dominated by counting statistics from shot noise.**

**In 11 hours, measure the asymmetry with the spin flipper and LEDs to be: $A_{\gamma} = (-8\pm5)\times10^{-9}$**

$$\vec{n} + p \rightarrow d + \gamma$$

## Status

- The measured moderator brightness is 2x smaller than predicted in 1997 when the experiment was proposed.
- The proton beam current is 2x smaller than anticipated in 1997: ~100 rather than 200 μA. (Increased severity of operational regime.)
- The $^3$He polarization and cell size are somewhat smaller than projected. Attenuations, etc. also.
- Field interference from FP11A 11 T superconducting magnet.
- These factors taken together will result in a 3-fold increase in the statistical error achievable at LANSCE. (Estimated systematic errors remain negligible.)

## Schedule

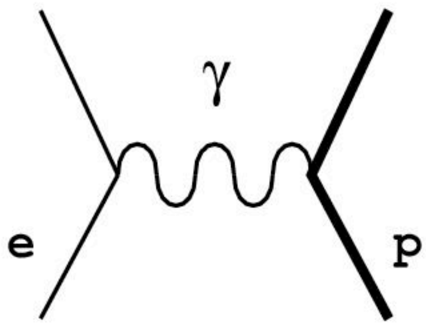
- Complete cave construction by end of 2003.
- Install and commission experiment January-April 2004.
- Install hydrogen target Summer 2004.
- Production data in 2004, 1000 hrs--> $A_\gamma$ to ± $5\times10^{-8}$.
- Move experiment to CG4 beamline at HFIR (Oak Ridge)

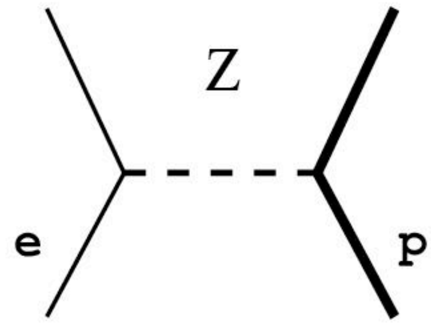
# Experimental Differences

| NPDGamma | Qweak |
| --- | --- |
| 10-20% at best | 4% |
| Test of meson exchange model for HWI | Standard Model test of $\sin^2\theta_W$ |
| polarized n capture | polarized e- scattering |
| polarization in apparatus, reversal in apparatus | polarization at source, reversal at source |
| low power para- H target | 2 kW H target |
| CsI scintillators | synthetic quartz Cerenkov |

## Physics background

The weak charge of the proton has never been measured.
Parity violation in polarized elastic electron-proton scattering at forward angles & low $Q^2$ isolates A(e) x V(p): $Q^p_{weak}$




$$\text{Asymmetry} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx \frac{M_{NC}}{M_{EM}} \xrightarrow{Q^2 \to 0} \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q^p_{weak} + Q^4 B\left(Q^2\right)\right] \approx -0.3 \text{ ppm}$$

@ $Q^2$=0.03 GeV$^2$

weak charge of the proton

electromagnetic and weak form factors suppressed by the $Q^4$ for low energy scale (contribute -0.1 ppm at $Q^2$=0.03 GeV$^2$)

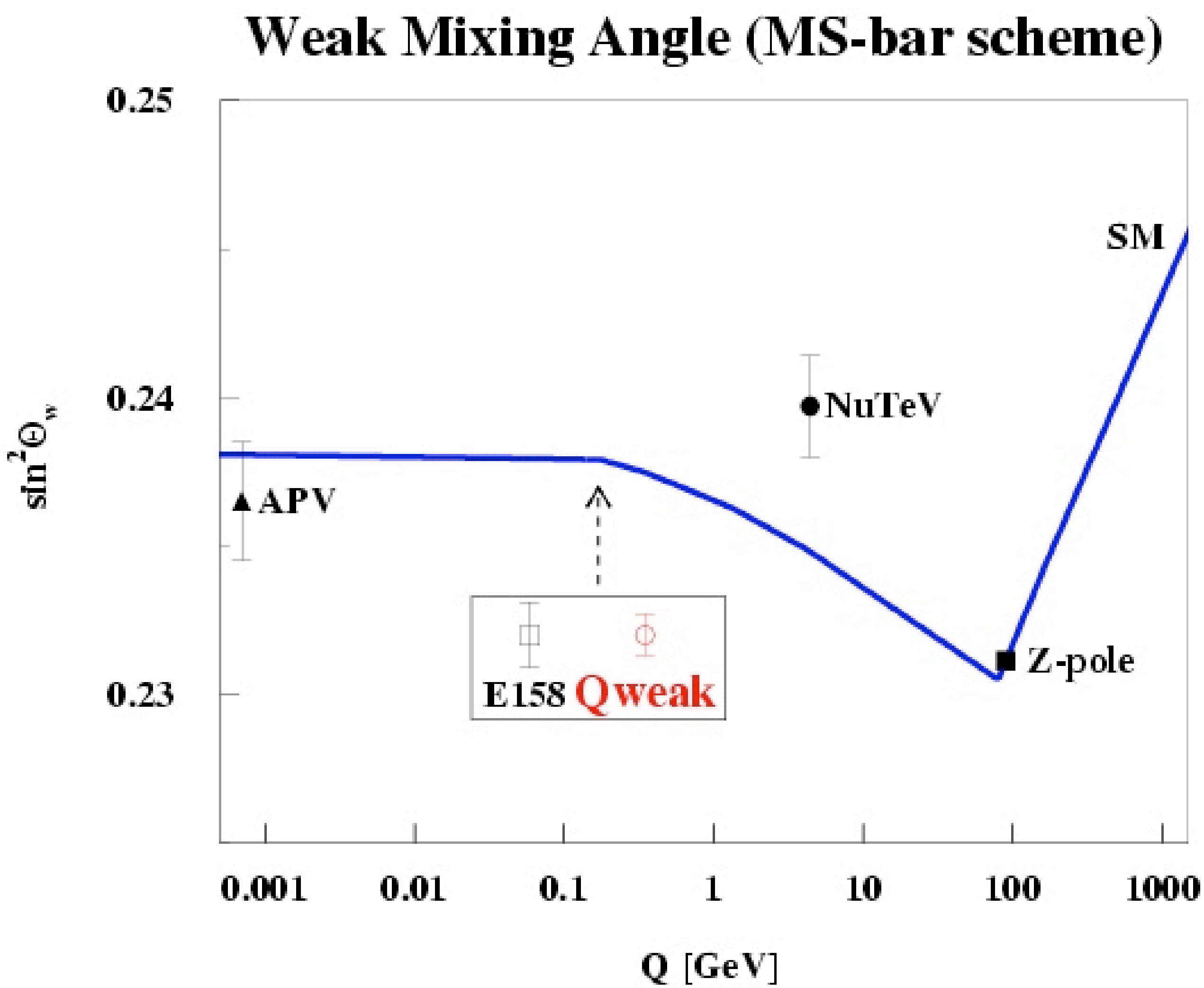
**$Q^p_{weak}$ is a well-defined model-independent experimental observable with a definite prediction in the electroweak Standard Model**

JLab E02-020

Measure the parity-violating asymmetry in e-p elastic scattering at $Q^2 = 0.03\ \mathrm{GeV}^2$ to 4% relative accuracy

Extract the proton weak charge: $Q^p_{weak} = 1 - 4\sin^2\theta_W \sim 0.072$

**Running of $\sin^2\theta_W$ in the Standard Model**



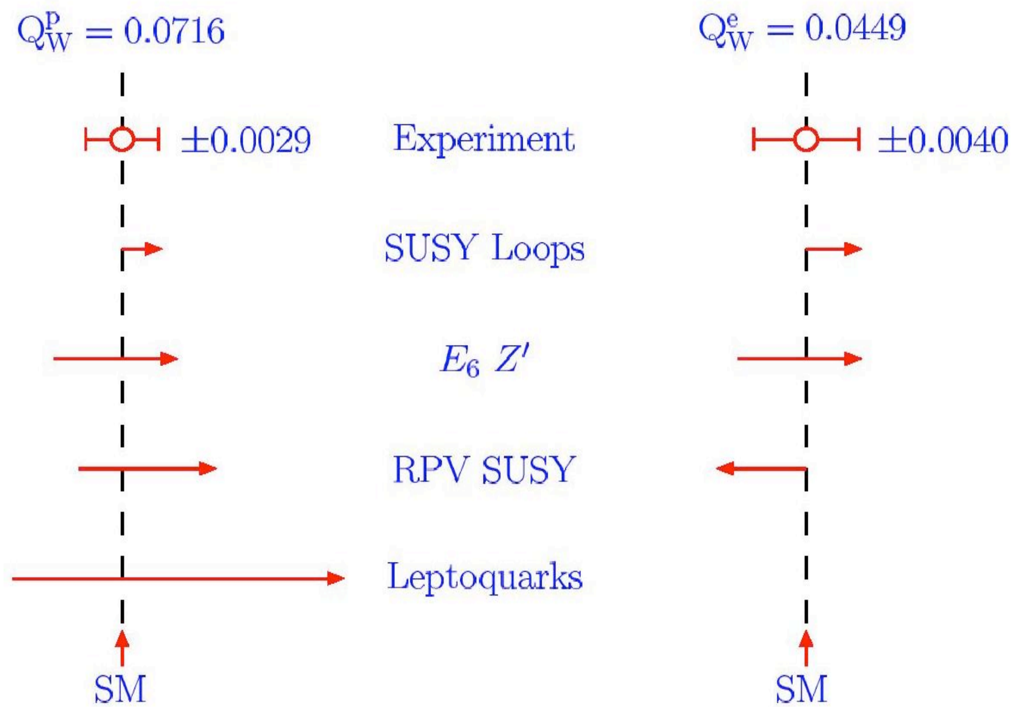

[plot courtesy J. Erler, A. Kurylov, M.J. Ramsey-Musolf, Phys. Rev. **D68** 016006 (2003)]

**Qweak**

*e-p* scattering

SLAC E158

*e-e* scattering




# New physics?

[figure courtesy J. Erler, A. Kurylov, M.J. Ramsey-Musolf, Phys. Rev. **D68** 016006 (2003)]

# Energy Scale of an Indirect Search for New Physics

• Parameterize New Physics contributions to PV scattering in electron-quark Lagrangian

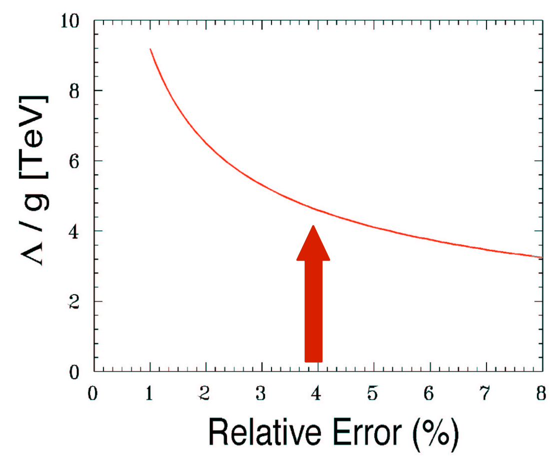
$$\mathcal{L}^{PV}_{e\text{-}q} = \mathcal{L}^{PV}_{SM} + \mathcal{L}^{PV}_{NEW} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e\sum_q C_{1q}\bar{q}\gamma^\mu q + \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e\sum_q h_V^q\bar{q}\gamma^\mu q$$

$g$ : coupling constant

$\Lambda$ : mass scale

• A 4% $Q^p_{weak}$ measurement probes for new physics at energy scales up to:

$$\frac{\Lambda}{g} \approx \frac{1}{\sqrt{\sqrt{2}G_F\left|\Delta Q_W^p\right|}} \approx 4.6\ \text{TeV}$$




• $Q_{weak}$ results consistent with the Standard Model will eliminate many candidate extensions.

• The TeV discovery potential of $Q_{weak}$ will be unmatched until LHC operation begins.

# Nucleon Structure Contributions to the Asymmetry

Quadrature sum of expected $A_{hadronic}$ and $A_{axial}$ errors contributes ~2% to error on $Q^p_W$ -- dominant systematic

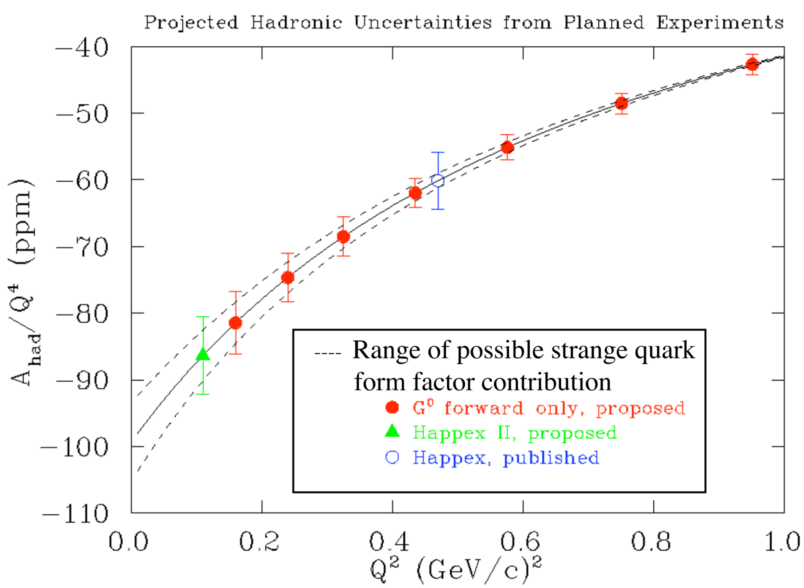
At $Q^2 = 0.03$ GeV$^2$

$$A = A_{Q_W^p} + A_{hadronic} + A_{axial}$$

= .19 ppm  .09 ppm  .01 ppm

hadronic: (31% of asymmetry)
Contains $G^{}_{E,M}$ $G^Z_{E,M}$
Will be constrained
by HAPPEX, $G^0$, MAMI A4

axial: (3.5% of asymmetry)
Contains $G^e_A$, has large
electroweak radiative corrections
Will be constrained by $G^0$ and SAMPLE




Expected constraints on $A_{hadronic}$ from upcoming experiments

# The $Q_{weak}$ Collaboration – JLab Experiment E-02-020

D. Armstrong, T. Averett, J. Birchall, J.D. Bowman, R. Carlini, S. Chattopadhyay, C.A. Davis, J. Dunne, J. Erler, R. Ent, W. Falk, J.M. Finn, T.A. Forest, D. Gaskell, K. Grimm, C. Hagner, W. Hersman, M. Holtrop, K. Johnston, R. Jones, C. Keppel, E. Korkmaz, S. Kowalski, L. Lee, A. Lung, D. Mack, S. Majewski, G.S. Mitchell, H. Mkrtchyen, N. Morgan, A. Opper, S.A. Page, S.I. Penttila, M. Pitt, B. M. Poelker, T. Porcelli, W.D. Ramsay, M. Ramsey-Musolf, J. Roche, N. Simicevic, G. Smith, R. Suleiman, S. Taylor, W.T.H. van Oers, S. Wells, W.S. Wilburn, S.A. Wood, C. Zorn

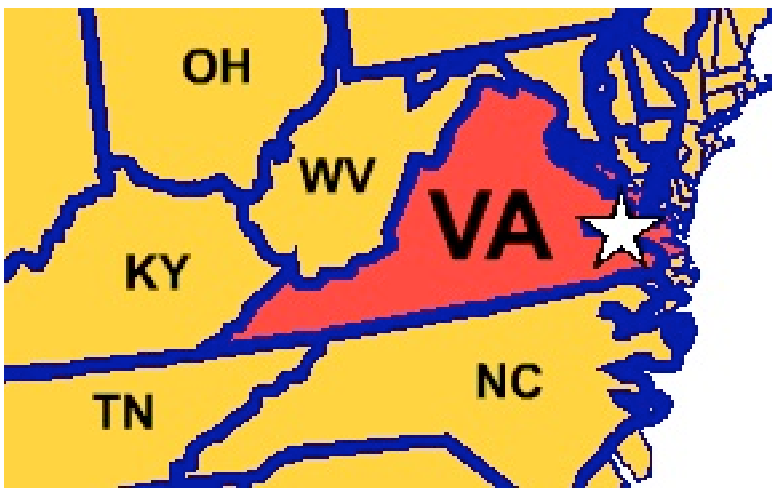
*Jefferson Lab, Caltech, U. Connecticut, Hampton U., Los Alamos National Laboratory, Louisiana Tech, U. Manitoba, M.I.T., Mississippi State, U. Nacional Autonoma de Mexico, U. New Hampshire, UNBC, Ohio U., TRIUMF, Virginia Tech, William & Mary, Yerevan*

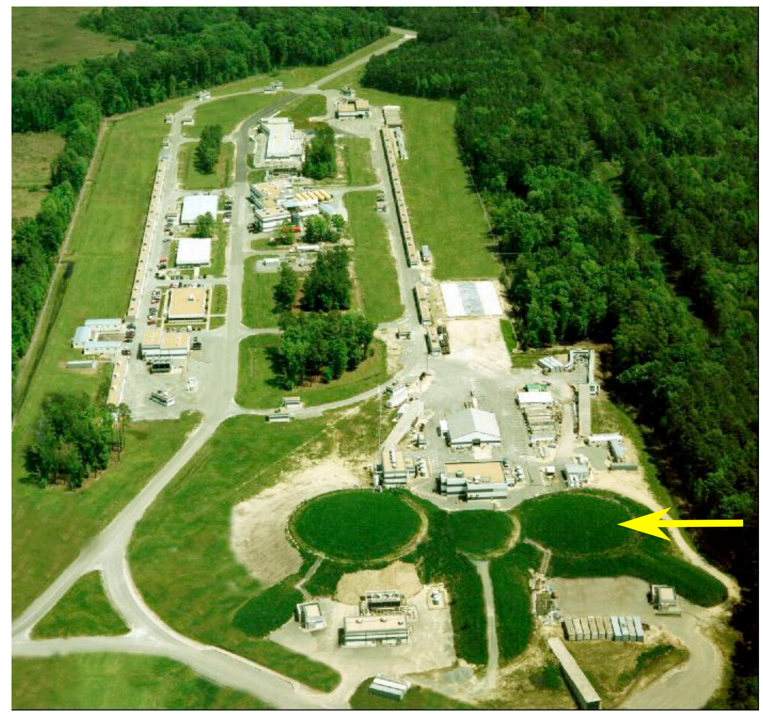
Spokespersons: R. Carlini (P.I.), J.D. Bowman, J.M. Finn, S. Kowalski, S.A. Page

| | |
|---|---|
| May 2000 | Collaboration formed |
| July 2001 | JLab Letter of Intent |
| January 2002 | JLab Proposal Approved with ‘A’ rating |
| January 2003 | Technical Design Review strongly endorses technical approach |
| Summer 2003 | Formal funding requests submitted to DOE, NSF & NSERC |
| Late 2006 | Experiment construction complete |
| 2007 | Run I (23 days) |
| 2008 | Run II (93 days) |

# Thomas Jefferson National Accelerator Facility

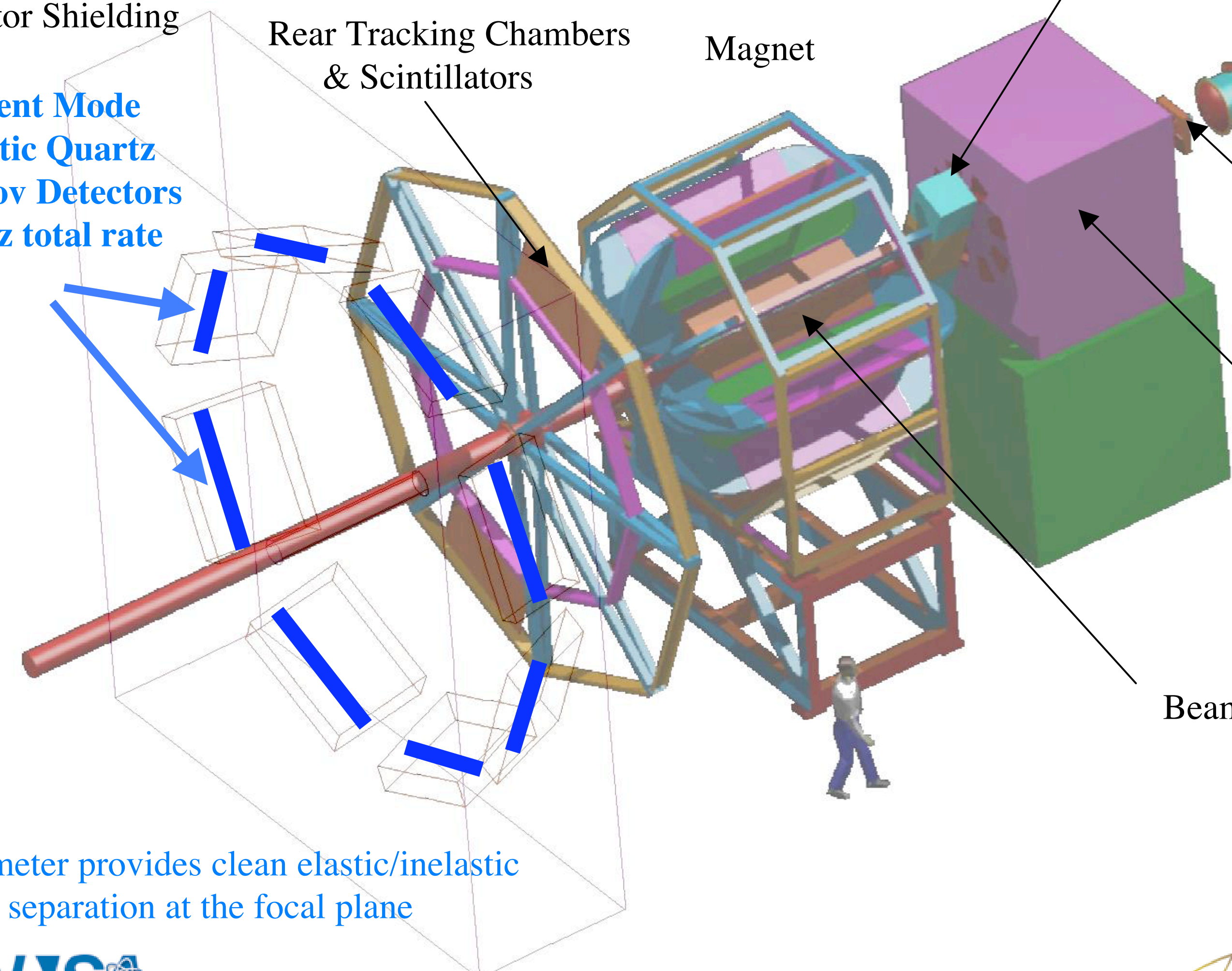
**Newport News, VA**



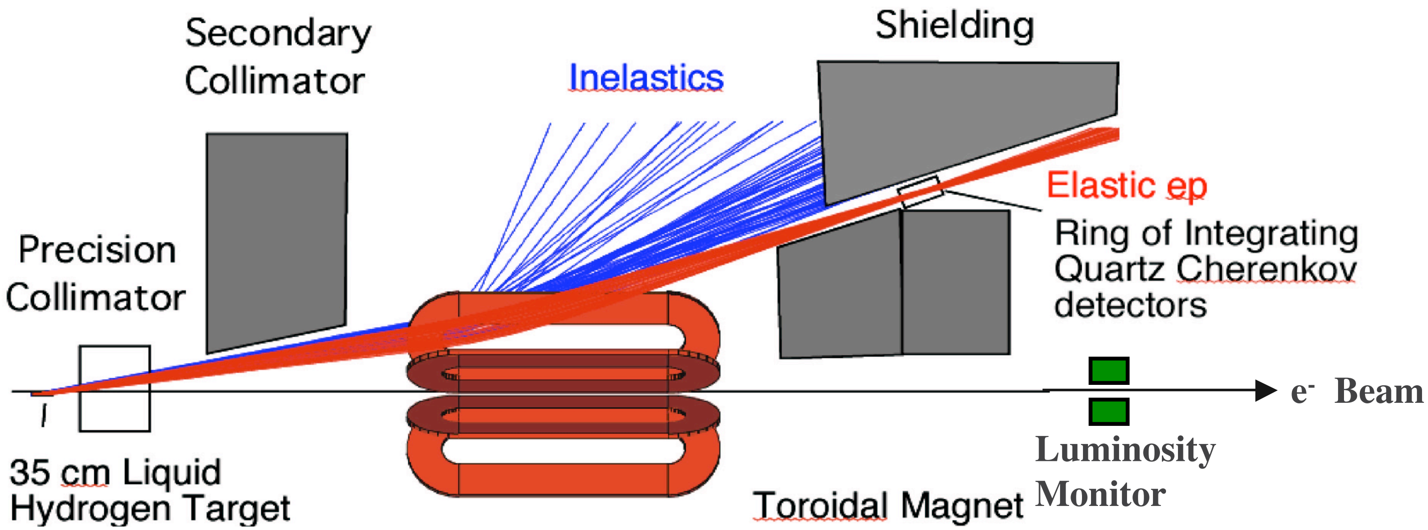
**Hall C**

# Illustration of the $Q_{weak}$ Experiment




spectrometer provides clean elastic/inelastic electron separation at the focal plane

# $Q_{weak}$ Experimental Overview




Experimental parameters:

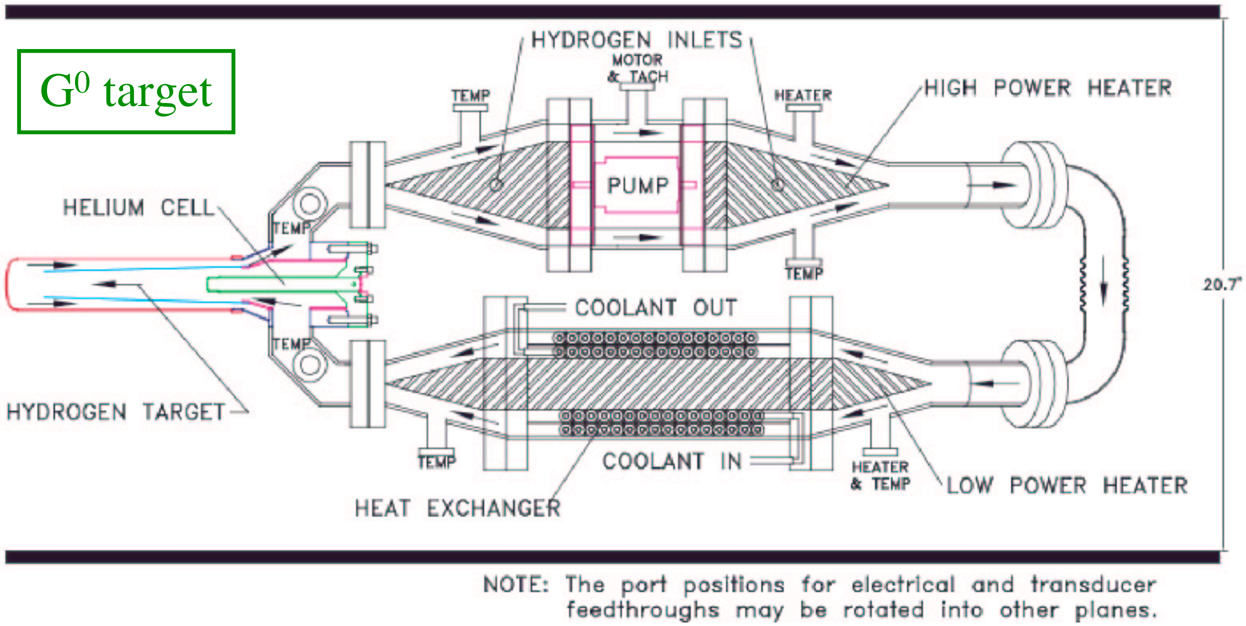
| | |
|---|---|
| Incident beam energy | 1.165 GeV |
| Beam Current | 180 μA |
| Beam Polarization | 80% |
| Running Time | Run I 23 days |
| | Run II 93 days |

| | |
|---|---|
| Central scattering angle | 9° |
| Scattering angle acceptance | ± 2° |
| Phi Acceptance | 67% of 2π |
| Solid angle | 46 msr |
| Average $Q^2$ | 0.03 GeV$^2$ |
| Integrated Rate (all sectors) | 6.1 GHz |
| Integrated Rate (per detector) | 0.8 GHz |
| Acceptance averaged asymmetry | –0.3 ppm |
| Statistical error per pulse pair | 5 x $10^{-5}$ |

# $Q_{weak}$ Liquid Hydrogen Target

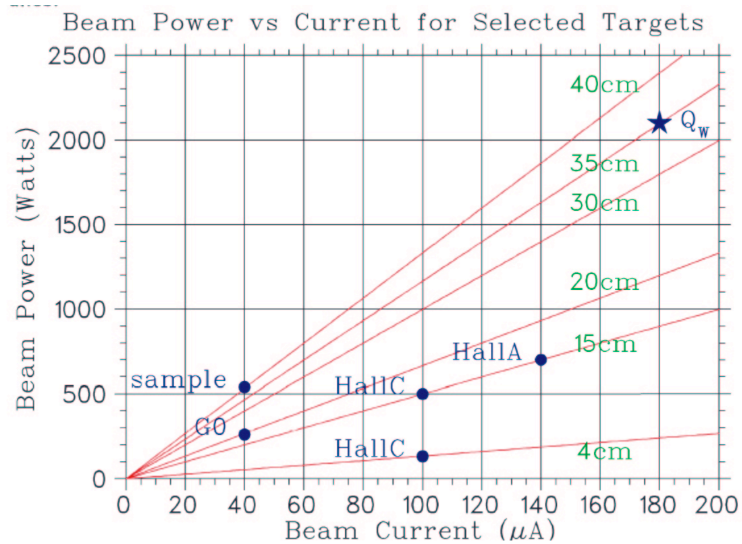
Similar in design to SAMPLE and $G^0$ targets

- longitudinal liquid flow
- high stream velocity achieved with perforated, tapered "windsock"




**$Q_{weak}$ target parameters/requirements:**

- length = 35 cm
- beam current = 180 μA
- beam power = 2200 W
- raster size ~4 mm x ~4 mm square
- flow velocity > 700 cm/s
- density fluctuations (at 15 Hz) < $5\times10^{-5}$



# $Q_{weak}$ Resistive Magnet: QTOR

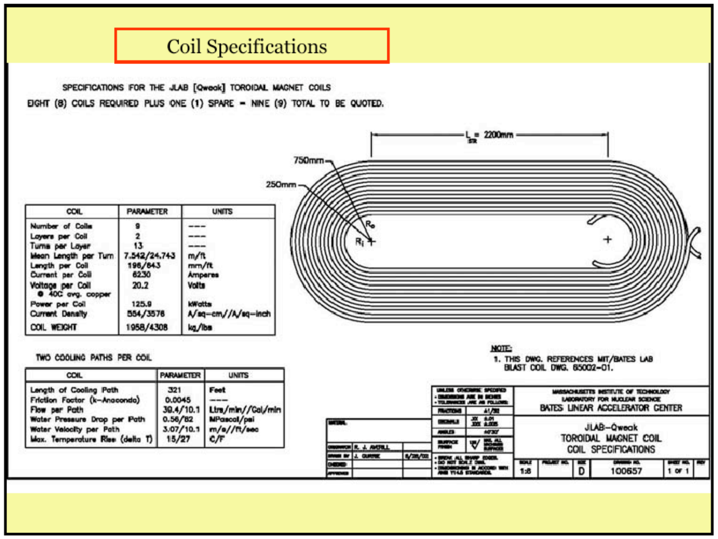
Manitoba//TRIUMF/M.I.T./Bates

Simple, reliable, inexpensive,
no negative coil curvature,
rapidly procurable (<18 months).

Exploits previous BLAST
engineering expertise.

Cost estimate:  790$K -- funded NSERC
(conductor, cables, fabrication,
support structure, power supply).

Electricity cost (full expt.):  180$K.



Coil Specifications

SPECIFICATIONS FOR THE JLAB [Qweak] TOROIDAL MAGNET COILS

EIGHT (8) COILS REQUIRED PLUS ONE (1) SPARE - NINE (9) TOTAL TO BE QUOTED.

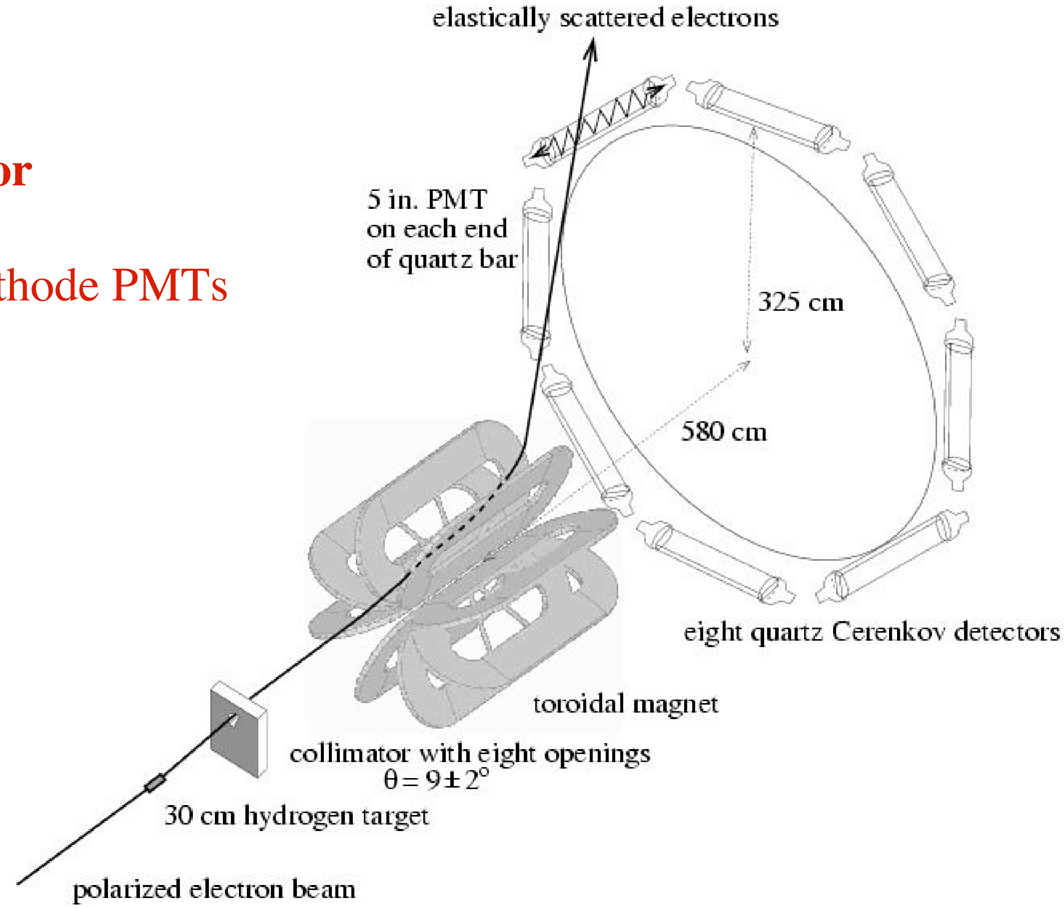
| COIL | PARAMETER | UNITS |
|---|---|---|
| Number of Coils | 9 | ---- |
| Layers per Coil | 2 | ---- |
| Turns per Layer | 13 | ---- |
| Mean Length per Turn | 7.542/24.743 | m/ft |
| Length per Coil | 196/643 | mm/ft |
| Current per Coil | 8230 | Amperes |
| Voltage per Coil @ 40C avg. copper | 20.2 | Volts |
| Power per Coil | 125.9 | kWatts |
| Current Density | 554/3578 | A/sq-cm//A/sq-inch |
| COIL WEIGHT | 1958/4308 | kg/lbs |

TWO COOLING PATHS PER COIL

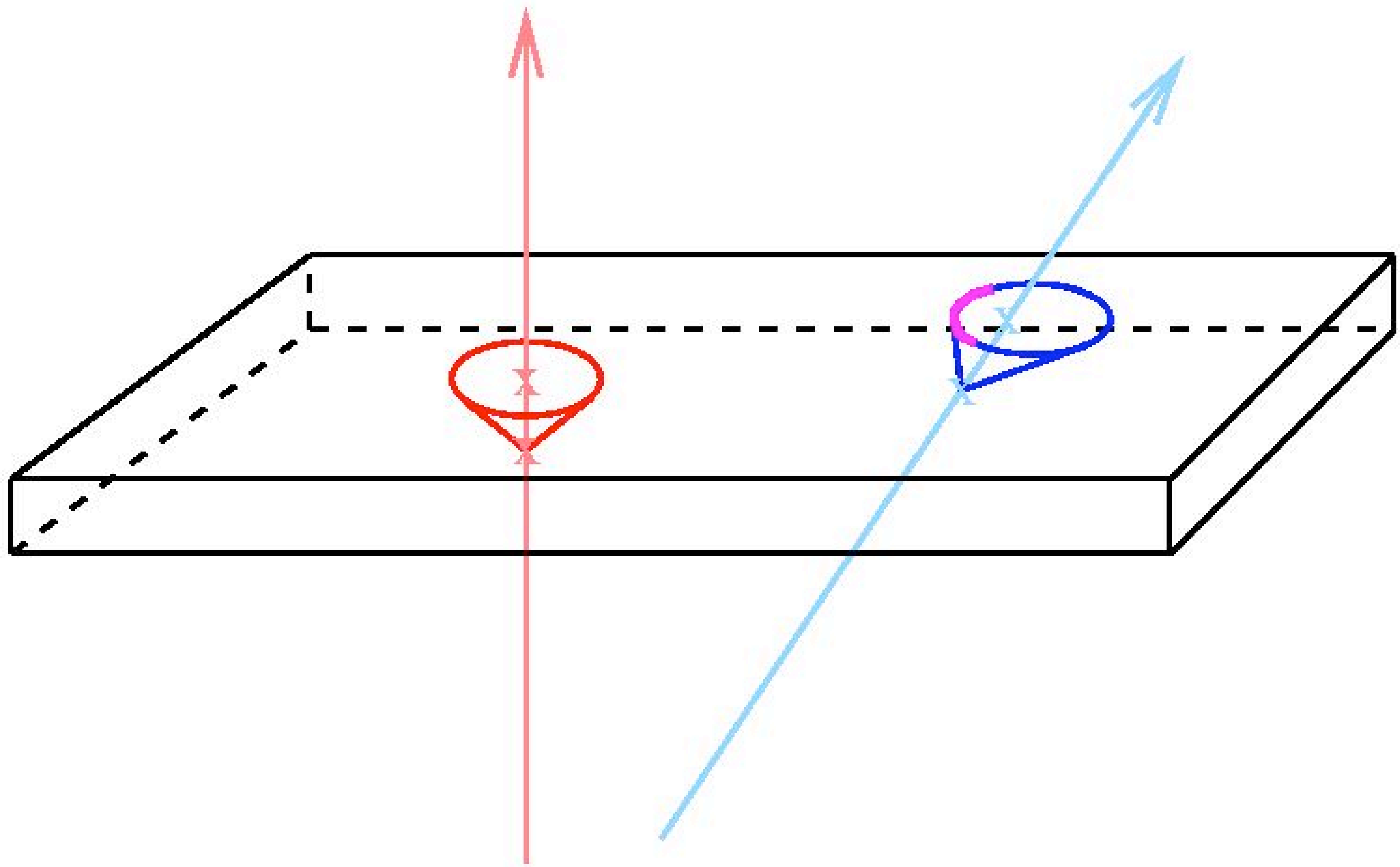
| COIL | PARAMETER | UNITS |
|---|---|---|
| Length of Cooling Path | 321 | Feet |
| Friction Factor (k-Anaconda) | 0.0045 | ---- |
| Flow per Path | 38.4/10.1 | Ltrs/min//Gal/min |
| Water Pressure Drop per Path | 0.56/82 | MPascal/psi |
| Water Velocity per Path | 3.07/10.1 | m/s//ft/sec |
| Max. Temperature Rise (delta T) | 15/27 | C/F |

# Current mode detection of elastically scattered e$^-$ in eight synthetic quartz Cerenkov detectors

**Synthetic Quartz Cerenkov Detector**
12 cm x 200 cm x 2.5 cm quartz bars
read out at both ends by S20 photocathode PMTs
(expect ~ 100 pe/event)



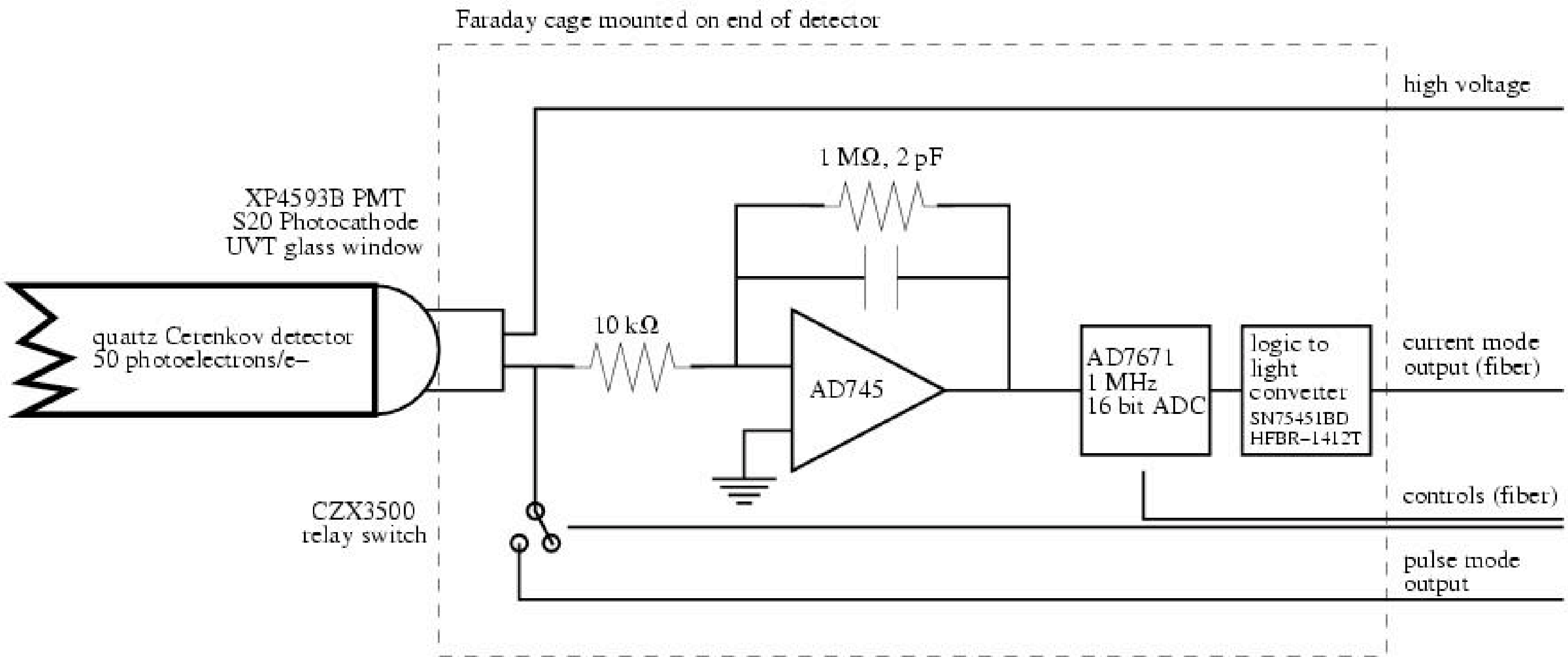
Acceptance of Cerenkov cone for total internal reflection



Normally incident electron - entire cone is internally reflected

Electron incident at angle - **part of cone** is too steep

# Front End Electronics




50 photoelectrons/e- x 0.7 GHZ = 6 nA cathode current

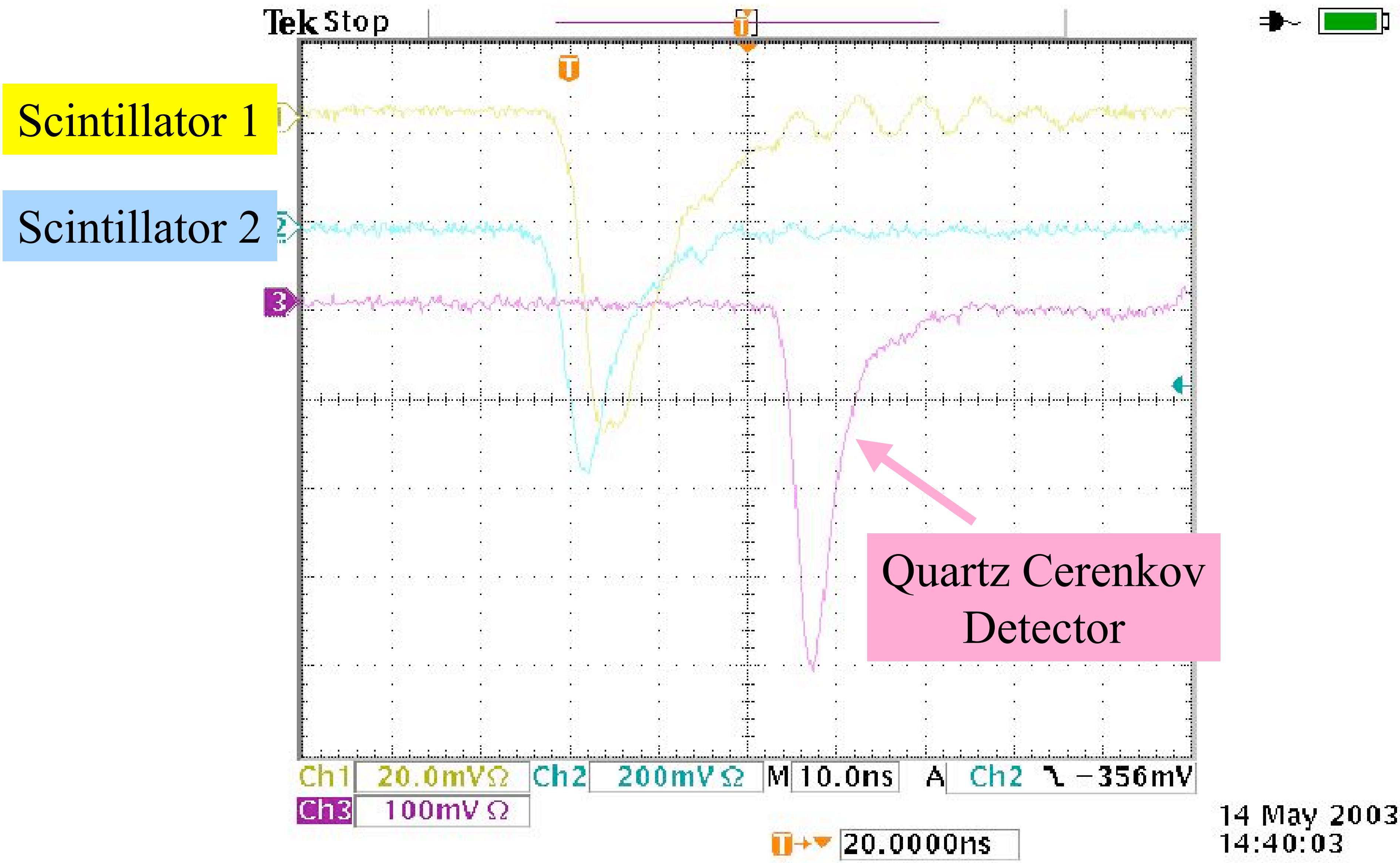
run PMT at gain of 1000, then gain of $10^6$ in low-noise amplifier = 6 V

- Normal operation in current mode
- Connection for auxiliary pulse mode (50 ▯ cable, and turn up HV)
- Negligible pickup
  - Surrounded by Faraday cage
  - Only one ground to each package
  - Optically isolated from DAQ
- Low electronic noise contribution compared to counting statistics
- 1 MHz 16 bit ADC will allow for oversampling

1 m synthetic quartz bar

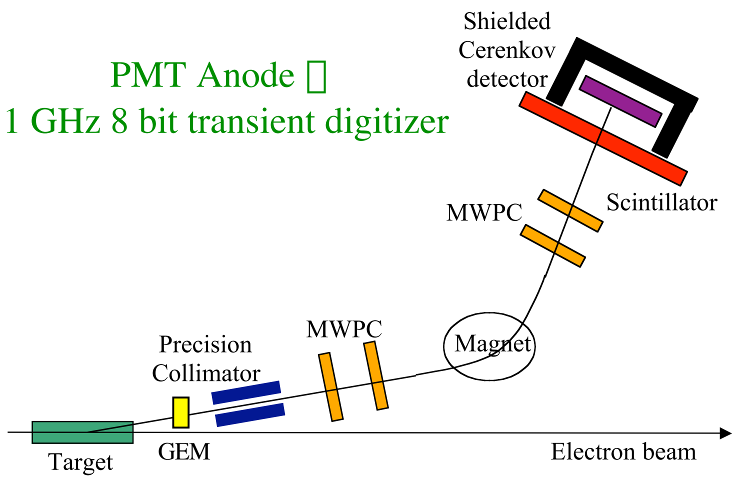
5” PMT

# Cosmic Rays in Quartz Cerenkov Detector



# Measurement of the Signal-to-Background Dilution Factor and Average $Q^2$

PMT Anode ⇒
1 GHz 8 bit transient digitizer




In current mode, no detector threshold exists
⇒ must know dilution factor

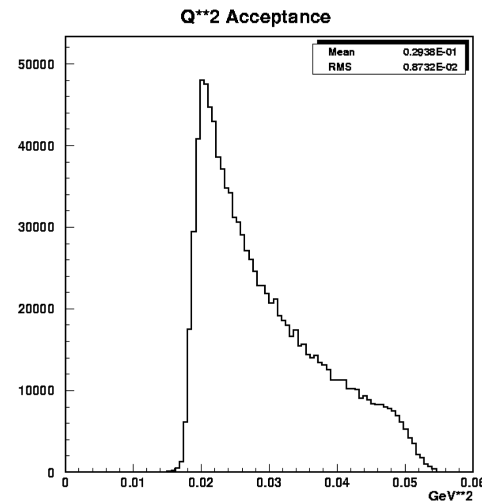
Dilution Measurement:

- Beam: 2 MHz (instead of 499), low current
- PMT anode read w/1 GHz 8-bit transient digitizer

Measure TOF distribution of the anode current
⇒ events of interest are in the prompt peak

Decompose Prompt Peak (into $e^-$ and background):

- Insert auxiliary MWPC's and scintillator
- Run at low beam current (pulse mode)
- Scintillator allows for neutral rejection
- MWPC's trace origin of scattered particles




Expected $Q^2$ distribution

Need to know $\delta\langle Q^2\rangle/\langle Q^2\rangle \sim 0.7\%$
requires survey accuracy ~ 1 mrad
(~ 2 mm for alignment of precision collimator with respect to the target)

- measure the shape of focal plane distribution
- measure position-dependent detector efficiency

# Anticipated Uncertainties on $Q_{weak}$

| | $\Delta Q^p_{weak}/Q^p_{weak}$ |
|---|---|
| Statistical (2200 hours) | 2.8% |
| Systematic: | |
| Measured hadronic structure corrections | 2.0% |
| Beam polarization | 1.4% |
| Average $Q^2$ determination | 1.0% |
| Helicity-correlated Beam Properties | 0.6% |
| Inelastic contamination under elastic peak | 0.2% |
| Target window Background | <1.0% |
| Total systematic | 2.9% |
| Total | 4.0% |

To do this requires:

- Detector, electronics, and target that allowing running at counting statistics limit
- Results from planned experiments ($G^0$, SAMPLE, HAPPEX, A4) to limit hadronic uncertainties
- Good beam polarimetry (Moller and Compton)
- Accurate measurement of average $Q^2$
- Accurate measurement of signal-to-background dilution factor
- Control of helicity-correlated beam properties along with null checks

# Other Important Issues Related to Systematics

1. Beam polarimetry
   - Hall C Basel Moller polarimeter, claimed absolute accuracy < 1.5%; collaboration working on running at higher currents.
   - Collaboration will install a Compton polarimeter in Hall C for continuous beam polarization monitoring.

2. Helicity-correlated beam parameters
   - Beamline instrumentation (stripline and microwave cavity monitors) exist from $G^0$.
   - Estimates of detector position, angle, and energy sensitivity indicate that the typical helicity-correlated beam parameters already achieved (under parity conditions) at JLab are sufficient.

3. Target window background
   - Potentially worrisome due to large (~4 $\sin^2\theta_W$) elastic $^{27}$Al asymmetry.
   - Can be measured directly (empty cell with thick windows) in few days to keep relative error <1%.
   - Collaboration is also investigating possibility of Beryllium windows.

JLab E02-020

# Status and Outlook

Status:

- Experiment is approved.
- Management plan and TDR complete.
- Collaboration continuing prototyping, moving towards final engineering.
- Once funding in place, anticipate ~3 years to construct full experiment.
- Goal:  first running (Run I = 23 days) in 2007.

Potential of $Q_{weak}$ Experiment :

- Precision measurement of the proton's weak charge.
- Fundamental measurement of the running of $\sin^2\theta_W$ at low energy.
- Sensitive search for new physics at the TeV scale.

# Summary

Many experiments are underway to study the weak interaction, using small to very small asymmetries.

(neutron $\beta$ decay & EDM [UCN's and beams], E158/G0/HAPPEX/PVA4)

The experiments require large statistics to achieve meaningful results, and careful attention to systematics
(especially spin correlated ones).